Baseline EEG theta/beta ratio and punishment sensitivity as biomarkers for feedback-related negativity (FRN) and risk-taking

Authors: Massar, Stijn.A.A.[1], Rossi, Valentina. [2,3], Schutter, Dennis. J.L.G.[1], & Kenemans, J. Leon.[1]

Affiliations:

1. Department of Experimental Psychology and Psychopharmacology, Helmholtz Institute, Utrecht University, Utrecht, the Netherlands

2. Department of Psychology University Milano-Bicocca**,** Milan**,** Italy

3. Department of Experimental clinical and health psychology, Ghent University, Ghent, Belgium

Dennis J.L.G. Schutter was supported by an Innovational Research Grant (452-07-012) from the Netherlands Organization for Scientific Research (NWO).

Address correspondence to:

Stijn A.A. Massar, MSc

Department of Experimental Psychology

Faculty of Social Sciences, Utrecht University

Van Unnik Building, Heidelberglaan 2

3584 CS Utrecht, The Netherlands

E-mail: stijnmassar@gmail.com

Phone: +31-30-2534368

Fax: +31-30-2534511

Abstract

Objective. Feedback-related negativity (FRN) is associated with reinforcement learning and punishment sensitivity. Furthermore, reinforcement learning proficiency can be predicted from pre-task baseline EEG theta/beta ratio. In this study it was examined whether there was a relation between baseline theta/beta ratio in rest and FRN amplitude during a gambling task, and if such a correlation would be related to theta activity or to beta activity.

Methods. Baseline EEG and a self-report measure of punishment sensitivity (BIS) were obtained from 52 healthy volunteers. FRN was recorded during a gambling task.

Results. FRN amplitude was negatively correlated with theta/beta ratio in high BIS individuals. Furthermore, source localization indicated that baseline theta activity generated in the anterior cingulate cortex (ACC) accounted for this correlation. For low BIS individuals no correlation was found.

Conclusion. An association between high baseline theta/beta ratio with low amplitude FRN and high risk-taking can be found in individuals who are sufficiently sensitive to punishments. This relationship is carried mostly by baseline theta activity, but not by beta activity.

Significance: This link between baseline brain activity, self-report measures and feedback processing may contribute to further understanding the biological basis of conditions that are accompanied by abnormal theta/beta ratio and reward processing, such as attention deficit hyper activity disorder (ADHD).

Key words: Feedback-Related Negativity, Baseline EEG, theta/beta ratio, Behavioral Inhibition System, risk taking, source localization

Highlights:

- Baseline EEG theta/beta ratio is associated with decreased feedback-related negativity and increased risk-taking during a gambling task.
- This association is only present in individuals with sufficiently high punishment sensitivity (BIS).
- Theta activity that is associated with decreased feedback-related negativity and increased risk-taking during a gambling task originates from the anterior cingulate cortex.

1. Introduction

Background brain activity as measured in baseline EEG shows individual differences in spectral power profiles. These differences are found to be highly stable over time and are therefore thought to reflect basic physiological properties of brain function (Corsi-Cabrera et al., 2007, Williams et al., 2005). As such, baseline EEG profiles have been related to personality traits and affective styles (e.g. Coan and Allen, 2004, Hewig et al., 2006, Jausovec and Jausovec, 2007). Interestingly, the relative contribution of slow wave theta activity (4-7 Hz) compared to fast wave beta activity (13-30 Hz), quantified as theta/beta ratio, has been related to impulsive behavior such as faster responding (van Dongen-Boomsma et al., 2010), and lower response inhibition (Putman et al., 2010). Furthermore, high theta/beta ratio has been associated with increased risk taking in the Iowa Gambling Task (Schutter and Van Honk, 2005). These findings point towards a relation between baseline theta/beta ratio and behavioral inhibition, such that people with high theta/beta ratios are more impulsive and tend to take higher risks. This idea is all the more interesting since increased theta/beta ratio and theta power are common features of attention-deficit/hyperactivity disorder (ADHD; Clarke et al., 2002b, di Michele et al., 2005, Snyder and Hall, 2006), a condition that is characterized by impulsivity and risk taking (Ernst et al., 2003, Masunami et al., 2009, Sonuga-Barke et al., 2008).

It has been suggested that high theta/beta ratio mainly reflects increased power in the theta band (di Michele, Prichep et al. 2005; Snyder and Hall, 2006). Rodent studies show that theta EEG is generated for a large part in the septo-hippocampal system (Vertes and Kocsis, 1997). Efferent connections from the hippocampus transfer rhythmic theta activity to limbic cortical areas, including the cingulate cortex (Gray, 1982, Gray and McNaughton, 2000). Extended cortical areas have been associated with theta-frequency EEG activity during resting state in human EEG studies. A combined EEG and fMRI study found that resting state EEG

theta power correlated with BOLD activity in a network including frontal, parietal and medial cortical areas, with a maximum in the medial prefrontal cortex (Scheeringa et al., 2008). Using a distributed dipole source reconstruction method (LORETA) Clemens et al. (2010) showed that resting state theta EEG was mainly localized in medial parts of the cortex including the anterior cingulate cortex (ACC), medial frontal gyrus, posterior cingulate and precuneus.

Specifically, the medial frontal sources of theta activity may be of interest, since the medial frontal cortex including the ACC has been implicated in reinforcement learning and risk taking. During gambling tasks, negative voltage deflections have been observed after receiving performance feedback or reward/punishment information (Gehring and Willoughby, 2002, Miltner et al., 1997). Similar to baseline theta activity, this feedback related negativity (FRN) has a frontal midline scalp distribution and is thought to originate in the ACC (Gehring and Willoughby, 2002). The FRN is thought to be instrumental in learning from feedback information (Cohen et al., 2007, Frank et al., 2005, Hajcak et al., 2007, Holroyd and Coles, 2002, Nieuwenhuis et al., 2004). Individual differences in FRN amplitude have been related to risk taking and reinforcement learning proficiency (Frank et al., 2005, Franket al., 2007, Santesso et al., 2008), and to personality traits such as punishment sensitivity (Balconi and Crivelli, 2010, De Pascalis et al., 2010). The reinforcement learning theory of the FRN proposes that dopaminergic (DA) projections from the midbrain ventral tegmental area (VTA) transfer reward or error information to the ACC, causing pyramidal cells in the ACC to fire whenever the outcome of an action is worse than expected (Holroyd and Coles, 2002). Interestingly, it has been argued that baseline theta activity can also be modulated by dopaminergic inputs from the midbrain DA system into the septo-hippocampal system, at least in ADHD patients (di Michele, Prichep, 2005). Increased theta power in ADHD patients can be normalized by dopaminergic medication (along with a reduction of clinical symptoms)

(Clarke et al., 2002a, Clarke, Barry, 2002b). Given these similarities, it is possible that both EEG theta and the FRN during gambling represent activity in the reward circuit. As such, increased risk taking behavior for people with high baseline theta/beta ratio, as found by Schutter and van Honk (2005), may be mediated by sub-optimal error-feedback signaling.

The functional significance of baseline beta activity is less well known. It has been hypothesized to reflect cognitive mechanisms originating from widespread cortical areas (Schutter and van Honk, 2005). Investigations into whether baseline theta and baseline beta activity have separate contributions have, as yet, not been undertaken. In order to examine this in the present study, baseline theta and beta activity and theta/beta ratio were calculated from baseline EEG, and correlated with feedback-related EEG activity and risk-taking behavior during a gambling task. We first examined whether baseline theta/beta ratio was correlated to FRN amplitude and to risk-taking behavior. A negative correlation between theta/beta ratio and FRN amplitude, and a positive correlation between theta/beta ratio and risk-taking was expected. Secondly, in order to examine separate contributions of theta and beta activity to the expected correlations, the correlational analyses were repeated for baseline theta and beta power separately.

An additional point is that self-report measures of punishment sensitivity (Behavioral Inhibition System [BIS]; Carver and White, 1994) have been found to be related to FRN amplitude. Higher punishment sensitivity scores were associated with larger amplitude FRN (Amodio et al., 2008; De Pascalis, Varriale, 2010), and its response related counterpart, the error related negativity (ERN; Boksem et al., 2008, Boksem et al., 2006). The BIS was originally proposed by Gray as a neurophysiological system underlying aversive motivation, consisting of the septo-hippocampal system and its cortical projections (Gray, 1982; Gray and McNaughton, 2000). Activation in the BIS system in response to signals of punishment is thought to cause inhibition of ongoing, goal-directed actions. Individual differences in BIS

reactivity are commonly measured by self-report scales and are related to anxiety and negative affectivity (Carver and White, 1994). Given the neurophysiological overlap and the demonstrated relationships between BIS, theta activity and FRN, it is possible that the relationship between theta activity and FRN is modulated by punishment sensitivity. Self-report scores of BIS were collected, to examine the possibility of such a modulatory effect.

2. Methods

2.1. *Participants*

Fifty two subjects were recruited (mean age = 21.9, s.d. = 3.14, 24 males, 28 females) through flyers distributed at the university campus. Subjects were screened by means of a short interview to ensure they met inclusion criteria. All participants, except for one, were university students. All participants were healthy volunteers, and reported no psychiatric or neurologic disorders, nor brain trauma. Furthermore participants declared not to use drugs or psychoactive medication, and to have normal or corrected-to-normal vision. Informed consent was obtained and participants received payment for taking part in the study. The protocol was approved by the medical ethical committee of the University Medical Center in Utrecht, in accordance with the standards set by the Declaration of Helsinki.

2.2 *BIS / BAS questionnaire*

Behavioral Inhibition and Behavioral activation scores were obtained using the BIS/BAS questionnaire (Carver and White, 1994, Dutch translation by Franken et al., 2005). The BIS/BAS questionnaire is a 20-item questionnaire consisting of two scales, behavioral inhibition (BIS) and behavioral activation (BAS). Data from the BIS scale will be presented here. The BIS scale consists of seven items thought to assess punishment sensitivity or the

drive to avoid aversive events. The BIS scale has an inter-trial reliability of $\alpha = .74$ (Carver and White, 1994). Typical items of the BIS scale are: "I feel pretty worried or upset when I think or know somebody is angry at me", or "I worry about making mistakes". Items are answered on a four-point Likert scale, indicating to what extent the subject considers the statement in the given item to be true for him or herself. In this study, the BIS scale was used because it was previously found to be correlated to feedback-related and error-related electrophysiological activity (Balconi et al. 2010, Boksem et al., 2006, De Pascalis et al., 2010). A median-split procedure was used to classify participants as high BIS or low BIS.

2.2. *Gambling Task*

The gambling task as described by Gehring and Willoughby was applied (Gehring and Willoughby, 2002). Two squares, one containing the number 5 and the other the number 25, were presented to the left and the right, respectively, from a fixation cross. Participants had to choose one of the squares, in order to gamble for the corresponding amount (in Euro cents). After a 1-second delay the squares turned red or green, indicating loss or gain of the chosen amount. Feedback stayed on screen for 1 second. Participants were informed that the total amount that was gained in this task would be added to their compensation as a bonus. Outcome was determined in a random fashion to assure similar numbers of loss and win trials. The total number of trials was 160.

2.3. *EEG recording*

EEG signals were recorded with 64 Biosemi active electrodes (Biosemi, Amsterdam, the Netherlands), which were positioned according to the standard 10/10 EEG system. The outmost lateral positions were Fp1/Fp2, AF7/AF8, F7/F8, FT7/FT8, T7/T8, TP7/TP8, P9/P10, PO7/PO8, and O1/O2. Midline extended from Fpz to Iz. EOG electrodes were placed above

and below the left eye and on the outer canthi of each eye. Reference electrodes were placed on both mastoids, for offline re-referencing. The Biosemi active electrode system uses an active online referencing, through a Common Mode Sense and a Driven Right Leg electrode (MettingVanRijn et al., 1996). All data were recorded with a 512 Hz low-pass filter at a sampling rate of 2048 Hz, and data were stored for offline analysis.

2.4. *Procedure*

Upon entering the lab subjects signed informed consent, and received verbal instructions, after which the EEG electrodes were mounted. The recording session started with 4 minutes of baseline EEG (2 minutes eyes open and 2 minutes eyes closed), after which the gambling task was performed. At the end of the experimental session personality questionnaires were filled out. EEG preparation and recording, and the gambling task, together performance lasted approximately one hour.

2.5. *Data reduction and analysis*

Behavioral performance. Choice preference in the gambling task was quantified per subject as the overall proportion of high (25 cents) choices. Risk taking after a loss was quantified as the proportion of high choices after a preceding high loss (-25 cents) trial, and risk taking after winning as the proportion of high choices after a high win (+25 cents).

Baseline EEG. EEG data were analyzed using Brian Vision Analyzer software (Brain Products Gmbh, Germany). Baseline analysis was based on a previous study from our lab (Schutter and van Honk, 2005). Spectral power calculations were obtained from the 4 minutes baseline EEG (eyes open/eyes closed). Recorded data were offline re-referenced to the averaged signal of both mastoids, filtered with a 1 Hz high-pass filter and a slope of 24 dB/oct,

and a 30 Hz low-pass filter with a slope of 24 dB/oct, and segmented in 4 second epochs. Ocular artefact was controlled using the Gratton and Coles algorithm (Gratton et al., 1983). Activity that exceeded 60 μV between two subsequent sample points, or exceeded an absolute voltage of 80 μV, was considered an artefact, as was low activity of a 0.3 μV difference or less in a 50 ms time window. Segments containing artefacts were omitted from further analysis. A Fast Fourier Transform was performed using a 10% Hamming window. All segments were averaged to obtain spectral power. Absolute theta (4-7 Hz) power, beta (13-30 Hz) power, and the theta/beta ratio were estimated as average values in a frontocentral electrode cluster (FCz and four surrounding electrodes Fz, Cz, FC1, and FC2). To correct for non-normality EEG power values and ratio were log transformed (Putman et al., 2010). Separate analysis of eyes-open and eyes closed resting state theta and beta power in our sample demonstrated that eyes-open and eyes-closed power scores were highly correlated ($theta_{frontal\text{-}central}$: r = .895, p <001; $beta_{frontal\text{-}central}$: r = .913). Therefore we used an average score of eyes-open and eyes-closed power for further statistical analysis.

ERPs. ERP analysis was conducted following earlier studies from our lab (Massar et al., 2010). EEG data recorded during the gambling task were re-referenced offline to the averaged signal of both mastoids, and subsequently filtered with a 0.3 Hz high-pass filter and a slope of 24 dB/oct, a 30 Hz low-pass filter with a slope of 24 dB/oct and a 50 Hz notch filter. Data were segmented into 1600 ms windows with a 100 ms baseline with respect to the feedback stimulus onset. Ocular artefact was controlled using the Gratton and Coles algorithm (Gratton et al., 1983), and segments containing artefacts were removed (difference criterion between two subsequent data points of 60μV; differences criterion within segment of 100 μV; absolute amplitude criterion of 80μV). Average ERPs for loss and win trials separately, as well as a loss-win difference potential, were derived for each subject. Calculation of the FRN was based on methods described by Gerhing and Willoughby (2002). FRN amplitude was

quantified at midline electrodes (Fz, FCz, Cz and Pz) as the average amplitude of the difference wave in the 200-300 ms post-feedback-stimulus window. The use of a difference wave in FRN quantification is a common method. It must be noted that a disadvantage of using a difference wave is that resulting differences can be due to win-related activity or to loss-related activity. An advantage, on the other hand, is that it can accurately quantify the loss-win difference when no clear deflections are present in FRN latency window, as is often the case for win-locked ERPs.

Source localization. To evaluate whether neural sources of baseline theta or beta activity were correlated with FRN amplitude standardized low resolution brain electromagnetic tomography (sLORETA; Pascual-Marqui, 2002) was used. sLORETA computes standardized current density in a cortical grey matter solution space, based on the Montreal Neurological Institute (MNI) brain template. sLORETA does not presuppose any specific number of sources, but computes the smoothest possible solution, assuming that scalp recorded EEG is resulting from simultaneous activation of neighboring neurons. Current density was calculated at the peak latency of the FRN difference wave (255 ms, DC=0).

Statistical analysis. The relation between baseline theta/beta ratio and FRN amplitude was examined using analysis of covariance (ANCOVA) with Electrode (Fz, FCz, Cz, Pz) as within-subjects factor, BIS (low, high) as between-subjects factor, and theta/beta ratio and a BIS x theta/beta ratio interaction term as covariates. In case of significant interactions follow-up analyses were performed. All analyses were initially carried out with theta/beta ratio as predictor. To unravel the separate contributions of theta and beta power, analyses were repeated using either theta power or beta power as predictor. To examine the relation between baseline EEG and BIS to task performance, similar ANCOVA's were performed with performance scores as dependent variables, and BIS and Baseline EEG as predictors.

Statistical non-parametric mapping (SnPM; included in the sLORETA analysis package) was applied for all voxels to estimate the location of baseline theta and beta activity that correlated with FRN amplitude. The statistical nonparametric mapping (SnPM) method operates under the null-hypothesis that the correlation coefficient in each voxel (i.e. correlation of baseline EEG current density per voxel with FRN amplitude) is not different from zero. A probability distribution is constructed by running a large number of random permutations of the data (Nichols & Holmes, 2002). In this case a critical value can be determined for which the chance of occurring under the null-hypothesis is lower than a set alpha level. When the observed correlation coefficient in a voxel exceeds this critical value, the correlation for this voxel can be considered significant. Here, the number of random permutations was set to 2000 and alpha level was set at .05 (corrected for multiple comparisons). Correlations between FRN amplitude and baseline EEG current density were assessed. Results therefore indicate which sources of baseline EEG are significantly correlated with FRN amplitude. SnPM analyses were conducted for theta and beta activity separately.

3. Results

Insert Figure 1 about here

3.1. Scalp recorded EEG

Figure 1 shows the Feedback-related ERP waveforms (A), the scalp distribution of the FRN (B), and scalp distributions for theta, beta, and theta/beta (C). The FRN as well as theta/beta ratio and theta power featured a medial frontal distribution. In contrast, beta power was marked by discrete central and occipital maxima.

The ANCOVA for FRN revealed a significant BIS x theta/beta interaction effect ($F(1,48) = 7.46$, $p < .01$). Furthermore, there were significant main effects of electrode ($F(3,46) = 7.45$, $p < .01$), BIS ($F(1,48) = 5.9$, $p < .05$), and a marginally significant electrode x BIS interaction effect ($F(1,48) = 3.3$, $p = .057$). To further analyze the BIS x theta/beta interaction effect, Electrode x Theta/beta ANCOVA's were conducted for high and low BIS groups separately. In the low BIS group no main effect of theta/beta or interactions between electrode and theta/beta were found (F's < 1). In contrast, in the high BIS group theta/beta ratio was found to significantly predict FRN amplitude ($F(1,26) = 6.6$, $p < .05$). Correlations show that in the high BIS group high theta/beta ratio's were associated with low FRN amplitudes ($r = .48$, $p < .05$ at FCz; see Figure 2). The absence of an electrode x theta/beta interaction indicated that this correlation was not different across the four electrode locations.

Further examination of the electrode x BIS interaction showed that the high BIS group had a higher FRN amplitude than the low BIS group at Fz ($t(1,50) = 2.12$, $p < .05$), FCz ($t(1,50) = 2.11$, $p < .05$), and Cz ($t(1,50) = 2.4$, $p < .05$), but not at Pz ($p > .2$).

Insert Figure 2 about here

To investigate the possibility that the relation between baseline EEG theta/beta ratio and FRN amplitude in the high BIS group was due to either theta power alone or beta power

alone, the above described ANCOVA was repeated for theta and beta power separately. Entering theta power as a covariate yielded results that were highly similar to the analysis with theta/beta ratio. A marginally significant BIS x theta interaction ($F(1,48) = 3.4$, $p = .07$) was found. In addition, again significant main effects of electrode ($F(3,48) = 5.64$, $p < .05$), BIS ($F(1,48) = 3.46$, $p < .01$), and a marginally significant electrode x BIS interaction ($F(3,48) = 3.33$, $p = .056$) were observed. Follow-up analysis for high and low BIS separately showed a significant effect of theta power in the high BIS group ($F(1,25) = 9.14$, $p < .01$; r = .49, p < .01; see Figure 2), but not in the low BIS group ($F < 1$; r = .07, n.s.). A similar analysis with beta power as covariate did not show any significant main or interaction effects including beta power (p's >.1).[1]

3.2. Source localization

Source localization of the FRN sLORETA source localization was performed at the same FRN latency. This analysis showed highest current density in a medial frontal cluster, peaking in the cingulate gyrus (see Figure 3; peak MNI coordinates: x = 5, y = 0, z = 50; BA 24).

Insert Figure 3 about here

---

[1] Analysis of theta and beta power was conducted at the fronto-central location corresponding to the peak distribution of theta/beta ratio. This was done to evaluate the separate contributions of theta and beta to the theta/beta-FRN correlation at the sites at which theta/beta ratio was maximal. As an anonymous reviewer noticed, baseline beta power did not show the same fronto-central distribution, but rather a central and an occipital peak. However, repeating the ANCOVA analysis using beta power at central (Cz, C1, C2, FCz, CPz) or occipital electrode clusters (Oz, O1, O2, POz, PO3, PO4) also did not yield significant effects of beta power (all p values > .1).

SnPM regression analyses were conducted in sLORETA to examine whether specific sources of baseline theta and beta power were related to individual differences in FRN amplitude and BIS. This analysis showed that the current density for baseline theta was correlated with FRN amplitude in a cluster of voxels in the cingulate gyrus bilaterally (see Figure 3; right: five voxels peaking at MNI coordinates: x =10, y = 10, z =35; left: four voxels peaking at: x= -10, y = 15, z = 30) and in two voxels in the left post-central gyrus (MNI coordinates: x = -35, y = -30, z = 40; x = -35, y = -25, z = 40; respectively), for the high BIS group only. For the low BIS group, theta current density in none of the voxels was significantly correlated with FRN amplitude. A similar correlational analysis for baseline beta activity yielded no significant correlations between beta sources and FRN amplitude, neither for high nor for low BIS groups.

Insert Figure 4 about here

3.2.2. Behavioral data

The overall average proportion of high choices was 0.56 (*sd* = .14). Participants more often chose high gambles after losing a high amount (p = .62) than after winning a high amount (p = .53; $t(51) = 3.05$, $p < .005$). To examine the relationship between BIS and baseline EEG on the one hand and behavioral adjustment patterns on the other hand, proportions of high choices were entered into an analysis of covariance, with previous outcome (win, loss) as a within-subjects factor, BIS (high, low) as a between-subjects factor, and theta/beta ratio as covariate. Furthermore a BIS x theta/beta ratio interaction term was entered. This analysis yielded a marginally significant three-way interaction between Previous outcome, BIS, and Theta/beta ratio ($F(1,48) = 3.47$, $p = .069$), and no further main or interaction effects. To

examine this interaction further, follow-up ANCOVA's were carried out for BIS groups separately. Similar to the FRN analysis discussed above, in the low BIS group no significant effects of theta/beta ratio on behavior were noted (all F's < 1). In contrast, in the high BIS group a significant main effect of previous outcome was found ($F(1,25) = 7.44$, $p < .05$), as well as a significant interaction between previous outcome and theta/beta ($F(1,25) = 5.95$, $p < .05$). Correlation analysis in this group showed that theta/beta ratio predicted the proportion of high choices after high win trials ($r = -.41$, $p < .05$, see Figure 4), but not after high losses ($r = -.09$, n.s.). In the low BIS group no correlations were found between behavior and theta/beta ratio (all p's >.4).

Finally, the ANCOVAs for choice behavior with theta or beta power separately as covariates, did not reveal any significant main or interaction effects (all F's < 1). Also, no relation between the overall proportion of high choices and BIS and baseline EEG was found (all F's < 1.5).

Insert Figure 4 about here

---

4. Discussion

In this study we found that baseline EEG theta power and baseline theta/beta ratio correlated with feedback related ERP activity and risk taking during a gambling task. This correlation was modulated by self-reported punishment sensitivity (BIS). High baseline theta power (and theta/beta ratio) was associated with reduced amplitude of the feedback-related negativity (FRN), and increased risk taking following high gains, in individuals with relatively high punishment sensitivity scores. For individuals with low punishment sensitivity no such

correlations were present. In contrast to theta power, there were no correlations between baseline beta power and FRN amplitude.

The behavioral inhibition system is theorized to reflect the sensitivity to punishments or non-rewards (Gray, 1982). In the most recent version of Gray's theory, BIS is thought to be specifically active in conflict situations (Gray and McNaughton, 2000). One instance of conflict is a situation in which positive and negative reinforcement are equally probable and there is no certainty as to whether an action will lead to reward or punishment (as was the case in the present study; Leue and Beauducel, 2008). The present findings suggest that sufficient sensitivity to punishments is necessary to reveal the relationship between feedback-related electrophysiological reactivity (FRN) and baseline EEG theta activity.

High baseline theta/beta ratio was not only related to FRN, but also to risk-taking during the gambling task. Behavioral choice scores mirrored the FRN findings, in that no correlations between baseline EEG and choice tendencies was found in the low BIS group, whereas in the high BIS group there was in fact a positive correlation between theta/beta ratio and risk-taking. This relation was most pronounced for choices directly following high win trials. This might reflect that baseline theta/beta ratio reflects the propensity to perseverate after successful, rewarded actions. It is remarkable that behavioral risk-taking correlated with baseline theta/beta ratio, but not with theta or beta separately. In contrast, the correlation between theta/beta ratio and FRN amplitude could be explained by an underlying direct correlation between theta power and FRN amplitude. The finding that FRN amplitude correlated particularly with theta power, but risk-taking was only correlated with theta/beta ratio may indicate more factors are involved in directing behavioral choice. Whereas the FRN and theta power are physiologically closely related to each other, the FRN activity might represent just one step involved in the decision making process. The FRN may be a fast motivational or affective reaction to the detection of the reward prediction error. The further

decision process might be dependent on control mechanisms related to beta activity (Schutter and van Honk, 2005). The present data do provide support for the idea that theta activity and FRN generation are related to each other. However, it is not possible to draw strong conclusions about physiological mechanisms and functional significance of baseline beta power.

With respect to theta power the present study demonstrated that for high-BIS individuals the part of theta activity that correlated with FRN amplitude has its most likely generators in the ACC. This might indicate that synchronized oscillatory activity in the ACC at rest (as reflected in high amplitude theta power) restricts phasic firing of the ACC in reaction to feedback information. It should be noted that theta activity in the human baseline EEG has also been reported to have generators in more widespread cortical areas (Clemens et al., 2010; Scheeringa et al., 2008). The current source localization however shows that specifically the contribution from the ACC to scalp-recorded theta is correlated with the feedback-related negativity. A possible mediating mechanism for the relationship between baseline theta activity and FRN is the midbrain DA system. The dominant theory of the FRN states that the FRN results from dopaminergic error signals from the VTA to the ACC (Frank et al., 2006; Holroyd and Coles, 2002), although other neurotransmitters have been implicated in FRN generation as well (Jocham and Ullsperger, 2009). Furthermore, it has been argued that theta activity in the septo-hippocampal system can be modulated by inhibitory dopaminergic input from the midbrain DA system (di Michele et al., 2005; Gasbarri et al., 1997). It is possible that inter-individual variance in baseline theta power and FRN amplitude both reflect underlying individual differences in midbrain DA functioning. This idea however remains to be tested. It might be specifically interesting with respect to ADHD. Increased theta/beta ratio in ADHD patients has been reported to differentiate responders to dopaminergic medication from non-responders (Clarke et al., 2002 b,c). Furthermore,

treatment with DA medication normalizes excess theta in these patients (Clarke et al., 2002 a; Clarke et al., 2003). In the current study only healthy participants were included and therefore the results do not speak directly to issues of pathology.

In the present study we have focused on the relationship between error-feedback processing and EEG theta activity in baseline. Recently however, a considerably amount of research has investigated the link between dynamic, task-related theta activity and feedback and error processing. Event-related increases in theta power and theta phase synchrony after a response error (Luu et al., 2004; Trujillo and Allen, 2007) or after feedback (Cavanagh et al., 2010; Kamarajan et al., 2008; Marco-Pallares et al., 2008) have been repeatedly reported. Moreover, it has been proposed that FRN and ERN to a large extent reflect average phase-locked theta responses (Cohen et al., 2007; Luu et al., 2004; Trujillo and Allen, 2007). It should be noted that the negative relationship between FRN amplitude and baseline theta power (as presently found) cannot simply be an artifact of phase-locking of baseline theta activity after feedback. Phase-locking of high power baseline theta would result in high amplitude feedback-related ERPs. Instead, high theta power was associated with low amplitude FRNs. This implicates that an additional mechanism, besides phase locking, plays a role in FRN generation. Similar findings have been reported for the relation between baseline theta power and short-latency visual evoked potentials (Klimesch et al., 2004).

In conclusion, the present study provides support for the idea that a relation exists between baseline EEG activity and reward and loss processing. The hypothesized inverse correlation between baseline EEG (theta power and theta/beta ratio) and feedback related ERP activity was found. However, this correlation was modulated by self-reported punishment sensitivity (BIS). Among individuals scoring high on the BIS scale an inverse correlation between FRN amplitude and baseline theta activity (localized in the ACC) was found. No such correlation was found for individuals who had low scores on the BIS scale. Furthermore,

in line with earlier findings (Schutter and van Honk, 2005), high theta/beta ratio was associated with a behavioral measure of risk-taking (choosing higher-stake gambles after receiving reward feedback). Again, this relation was only present among participants that scored relatively high on BIS.

Acknowledgements: The authors like to thank Sandra Andraszewicz for assistance with data collection. Dennis J.L.G. Schutter was supported by an Innovational Research Grant (452-07-012) from the Netherlands Organization for Scientific Research (NWO).

5. References

Amodio DM, Master SH, Yee CM, Taylor SE. Neurocognitive components of the behavioral inhibition and activiation system: Implications for theories of self-regulation. Psychophysiology 2008;45:11-19.

Balconi M, Crivelli D. FRN and P300 ERP effect modulation in response to feedback sensitivity: The contribution of punishment-reward system (BIS/BAS) and Behaviour Identification of action. Neurosci Res 2010;66:162-172.

Boksem MAS, Tops M, Kostermans E, De Cremer D. Sensitivity to punishment and reward omission: Evidence from error-related ERP components. Biol Psychol 2008;79:185-192.

Boksem MAS, Tops M, Wester AE, Meijman TF, Lorist MM. Error-related ERP components and individual differences in punishment and reward sensitivity. Brain Res 2006;1101:92-101.

Carver CS, White TL. Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: The BIS/BAS scales. J Pers Soc Psychol 1994;67:319-333.

Cavanagh JF, Frank MJ, Klein TJ, Allen JJB. Frontal theta links prediction errors to behavioral adaptation in reinforcement learning. Neuroimage 2010;49:3198-3209.

Clarke AR, Barry RJ, Bond D, McCarthy R, Selikowitz M. Effects of stimulant medications on the EEG of children with attention-deficit/hyperactivity disorder. Psychopharmacology 2002a;164:277-284.

Clarke AR, Barry RJ, McCarthy R, Selikowitz M. EEG differences between good and poor responders to methylphenidate and dexamphetamine in children with attention-deficit/hyperactivity disorder. Clin Neurophysiol 2002b;113:194-205.

Clarke AR, Barry RJ, McCarthy R, Selikowitz M, Croft RJ. EEG differences between good and poor responders to methylphenidate in boys with the inattentive type of attention-deficit/hyperactivity disorder. Clin Neurophysiol 2002c;113:1191-1198.

Clarke AR, Barry RJ, McCarthy R, Selikowitz M, Brown CR, Croft RJ. Effects of stimulant medications on the EEG of children with Attention-Deficit/Hyperactivity Disorder Predominantly Inattentive type. Int J Psychophysiol 2003;47:129-137.

Clemens B, Bessenyei M, Fekete I, Puskás S, Kondákor I, Tóth M, Hollódy K. Theta EEG source localization using LORETA in partial epilepsy patients with and without medication. Clin Neurophysiol 2010;121:848-58.

Coan JA, Allen JJB. Frontal EEG asymmetry as a moderator and mediator of emotion. Biol Psychol 2004;67:7-50.

Cohen MX, Elger CE, Ranganath C. Reward expectation modulates feedback-related negativity and EEG spectra. Neuroimage 2007;35:968-978.

Corsi-Cabrera M, Galindo-Vilchis L, del-Río-Portilla Y, Arce C, Ramos-Loyo J. Within-subject reliability and inter-session stability of EEG power and coherent activity in women evaluated monthly over nine months. Clin Neurophysiol 2007;118:9-21.

De Pascalis V, Varriale V, D'Antuono L. Event-related components of the punishment and reward sensitivity. Clin Neurophysiol 2010;121:60-76.

di Michele F, Prichep L, John ER, Chabot RJ. The neurophysiology of attention-deficit/hyperactivity disorder. Int J Psychophysiol 2005;58:81-93.

Ernst M, Kimes AS, London ED, Matochik JA, Eldreth D, Tata S et al. Neural Substrates of Decision Making in Adults With Attention Deficit Hyperactivity Disorder. Am J Psychiatry 2003;160:1061-1070.

Frank MJ, D'Lauro C, Curran TIM. Cross-task individual differences in error processing: Neural, electrophysiological, and genetic components. Cognit Affect Behav Neurosci 2007;7:297-308.

Frank MJ, Santamaria A, O'Reilly RC, Willcutt E. Testing Computational Models of Dopamine and Noradrenaline Dysfunction in Attention Deficit/Hyperactivity Disorder. Neuropsychopharmacology 2006;32:1583-1599.

Frank MJ, Woroch BS, Curran T. Error-Related Negativity Predicts Reinforcement Learning and Conflict Biases. Neuron 2005;47:495-501.

Franken IHA, Muris P, Rassin E. Psychometric Properties of the Dutch BIS/BAS Scales. J Psychopathol Behav Assess 2005;27:25-30.

Gasbarri A, Sulli A, Packard MG. the dopaminergic projections to the hippocampal formation in the rat. Prog Neuropsychopharmacol Biol Psychiatry 1997;21:1-22.

Gehring WJ, Willoughby AR. The Medial Frontal Cortex and the Rapid Processing of Monetary Gains and Losses. Science 2002;295:2279-2282.

Gratton G, Coles MG, Donchin E. A new method for off-line removal of ocular artifact. Electroencephalogr Clin Neurophysiol 1983;55:468-484.

Gray JA. The neuropsychology of anxiety: An enquiry into the functions of the septo-hippocampal system. Oxford, UK: Oxford University Press; 1982.

Gray JA, McNaughton N. The neuropsychology of anxiety. Oxford, UK: Oxford University Press; 2000.

Hajcak G, Moser JS, Holroyd CB, Simons RF. It's worse than you thought: The feedback negativity and violations of reward prediction in gambling tasks. Psychophysiology 2007;44:905-912.

Hewig J, Hagemann D, Seifert J, Naumann E, Bartussek D. The relation of cortical activity and BIS/BAS on the trait level. Biol Psychol 2006;71:42-53.

Holroyd CB, Coles MGH. The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. Psychol Rev 2002;109:679-709.

Jausovec N, Jausovec K. Personality, gender and brain oscillations. . Int J Psychophysiol 2007;66:215-224.

Jocham G, Ullsperger M. Neuropharmacology of performance monitoring. Neurosci Biobehav Rev 2009;33:48-60.

Jonkman LM, Kenemans JL, Kemner C, Verbaten MN, van Engeland H. Dipole source localization of event-related brain activity indicative of an early visual selective attention deficit in ADHD children. Clin Neurophysiol 2004;115:1537-1549.

Kamarajan C, Rangaswamy M, Chorlian DB, Manz N, Tang Y, Pandey AK, et al. Theta oscillations during the processing of monetary loss and gain: A perspective on gender and impulsivity. Brain Res 2008;1235:45-62.

Kemner C, Jonkman LM, Kenemans JL, Bocker KB, Verbaten MN, Van Engeland H. Sources of auditory selective attention and the effects of methylphenidate in children with attention-deficit/hyperactivity disorder. Biol Psychiatry 2004;55:776-778.

Kenemans JL, Lijffijt M, Camfferman G, Verbaten MN. Split-second sequential selective activation in human secondary visual cortex. J Cogn Neurosci 2002;14:48-61.

Klimesch W, Schack B, Schabus M, Doppelmayr M, Gruber W, Sauseng P. Phase-locked alpha and theta oscillations generate the P1-N1 complex and are related to memory performance. Brain Res Cogn Brain Res 2004;19:302-316.

Leue A, Beauducel A. A Meta-Analysis of Reinforcement Sensitivity Theory: On Performance Parameters in Reinforcement Tasks. Pers Soc Psychol Rev 2008;12:353-369.

Luu P, Tucker DM, Makeig S. Frontal midline theta and the error-related negativity: neurophysiological mechanisms of action regulation. Clin Neurophysiol 2004;115:1821-1835.

Marco-Pallares J, Cucurell D, Cunillera T, García R, Andrés-Pueyo A, Münte TF, et al. Human oscillatory activity associated to reward processing in a gambling task. Neuropsychologia 2008;46:241-248.

Massar SAA, Wester AE, Volkerts ER, Kenemans JL. Manipulation specific effects of mental fatigue: evidence from novelty processing and simulated driving. Psychophysiology 2010;47:1119-1126.

Masunami T, Okazaki S, Maekawa H. Decision-making patterns and sensitivity to reward and punishment in children with attention-deficit hyperactivity disorder. Int J Psychophysiol 2009;72:283-288.

MettingVanRijn AC, Kuiper AP, Dankers TE, Grimbergen CA. Low-cost active electrode improves the resolution in biopotential recordings. Conf Proc IEEE Eng Med Biol Soc 1996;1:101-102.

Miltner WHR, Braun CH, Coles MG. Event-related brain potentials following incorrect feedback in a time-estimation task: evidence for a "generic" neural system for error detection. J Cogn Neurosci 1997;9:788-798.

Mitchell DJ, McNaughton N, Flanagan D, Kirk IJ. Frontal-midline theta from the perspective of hippocampal "theta". Prog Neurobiol 2008;86:156-185.

Nieuwenhuis S, Holroyd CB, Mol N, Coles MGH. Reinforcement-related brain potentials from medial frontal cortex: origins and functional significance. Neurosci Biobehav Rev 2004;28:441-448.

Pascual-Marqui RD. Standardized low resolution brain electromagnetic tomography (sLORETA): technical details. Methods Find Exp Clin Pharmacol 2002; 24D:5-12.

Putman P, van Peer J, Maimari I, van der Werff S. EEG theta/beta ratio in relation to fear-modulated response-inhibition, attentional control, and affective traits. Biol Psychol 2010;83:73-78.

Santesso DL, Dillon DG, Birk JL, Holmes AJ, Goetz E, Bogdan R, et al. Individual differences in reinforcement learning: Behavioral, electrophysiological, and neuroimaging correlates. Neuroimage 2008;42:807-816.

Scheeringa R, Bastiaansen MC, Petersson KM, Oostenveld R, Norris DG, Hagoort P. Frontal theta EEG activity correlates negatively with the default mode network in resting state. Int J Psychophysiol 2008;67:242-251.

Scherg M, Berg P: Brain Electromagnetic Source Analysis, Version 3.0, Megis, Münich, 1998

Schutter DJLG, Van Honk J. Electrophysiological ratio markers for the balance between reward and punishment. Brain Res Cogn Brain Res 2005;24:685-690.

Segalowitz SJ, Santesso DL, Murphy TI, Homan D, Chantziantoniou DK, Khan S. Retest reliability of medial frontal negativities during performance monitoring. Psychophysiology 2010;47:260-270.

Snyder SM, Hall JR. A Meta-analysis of Quantitative EEG Power Associated With Attention-Deficit Hyperactivity Disorder. J Clin Neurophysiol 2006;23:441-456.

Sonuga-Barke EJS, Sergeant JA, Nigg J, Willcutt E. Executive Dysfunction and Delay Aversion in Attention Deficit Hyperactivity Disorder: Nosologic and Diagnostic Implications. Child Adolesc Psychiatr Clin N Am 2008;17:367-384.

Trujillo LT, Allen JJB. Theta EEG dynamics of the error-related negativity. Clin Neurophysiol 2007;118:645-668.

van Dongen-Boomsma M, Lansbergen MM, Bekker EM, Sandra Kooij JJ, van der Molen M, Kenemans JL, et al. Relation between resting EEG to cognitive performance and clinical symptoms in adults with attention-deficit/hyperactivity disorder. Neurosci Lett 2010;469:102-106.

Vertes RP, Kocsis B. Brainstem-diencephalo-septohippocampal systems controlling the theta rhythm of the hippocampus. Neuroscience 1997;81:893-926.

Williams LM, Simms E, Clark CR, Paul RH, Rowe D, Gordon E. The Test-retest Reliability of a standardized Neurocognitive and Neurophysiological test battery: "Neuromarker". Int J Neurosci 2005;115:1605-1630.

Figures

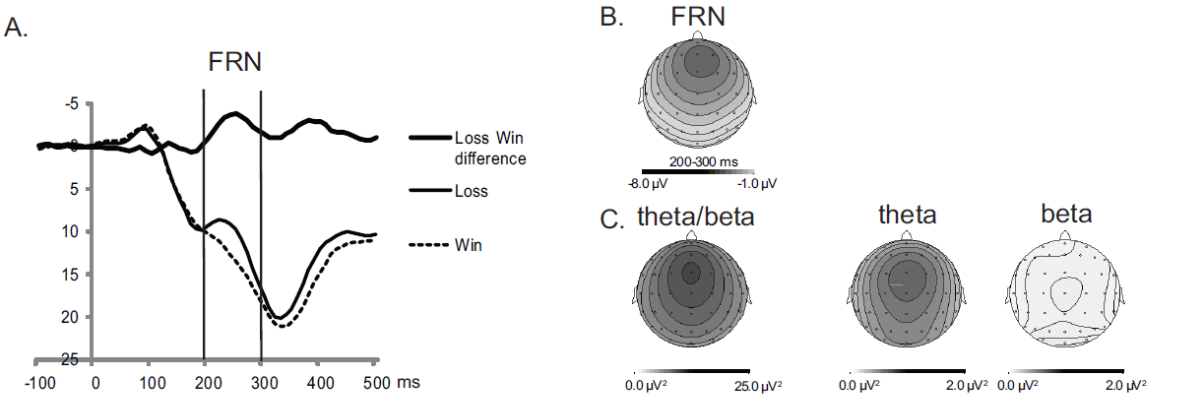

Figure 1. a) Feedback-locked waveforms at FCz. Time 0 indicates feedback onset, b) scalp distribution of FRN difference wave (200-300ms), c) scalp distributions for baseline EEG theta/beta ratio, theta power and beta power.

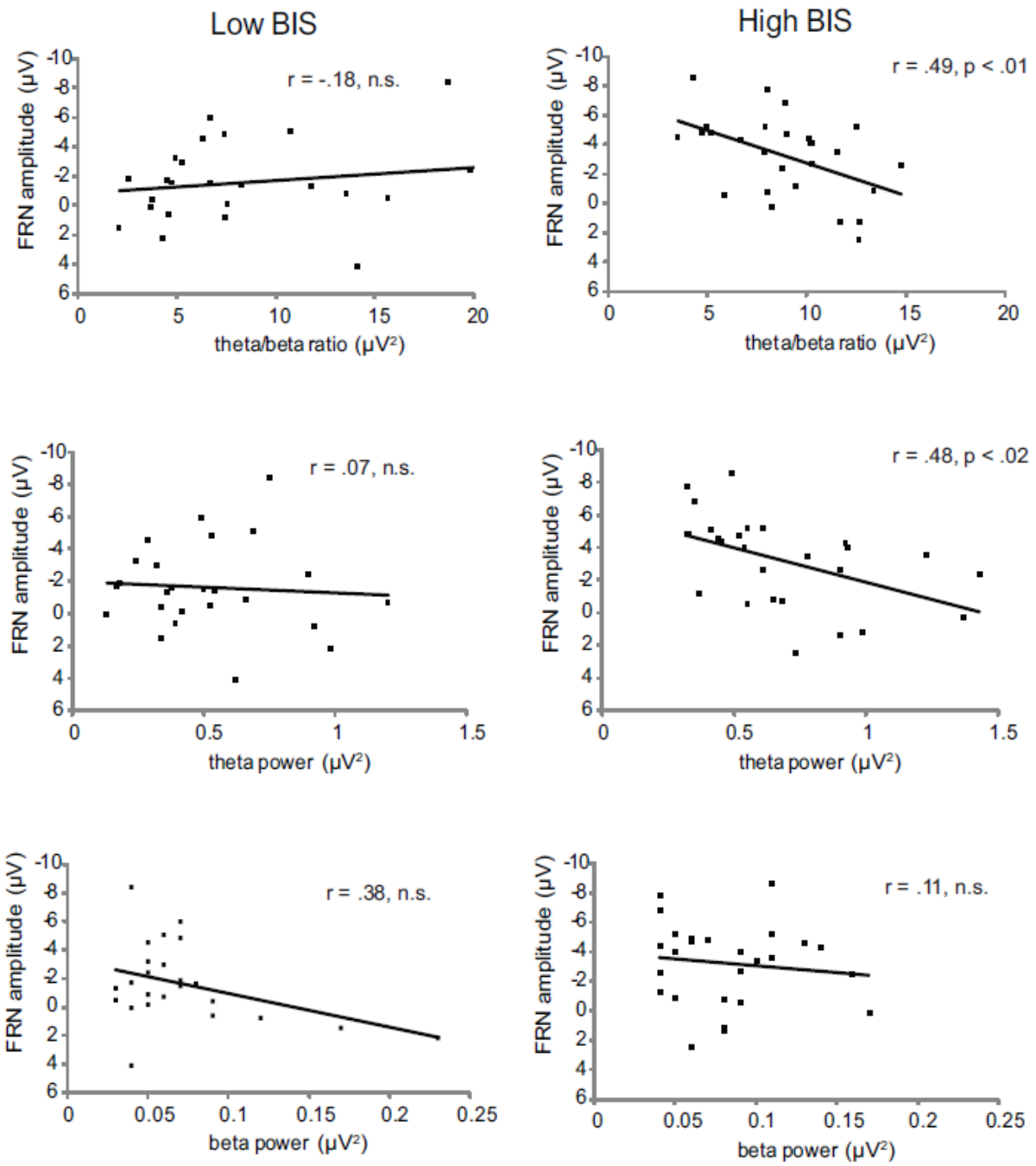

Figure 2. Correlations between FRN amplitude at FCz and baseline EEG theta/beta ratio and theta and beta power for high and low BIS participants separately.

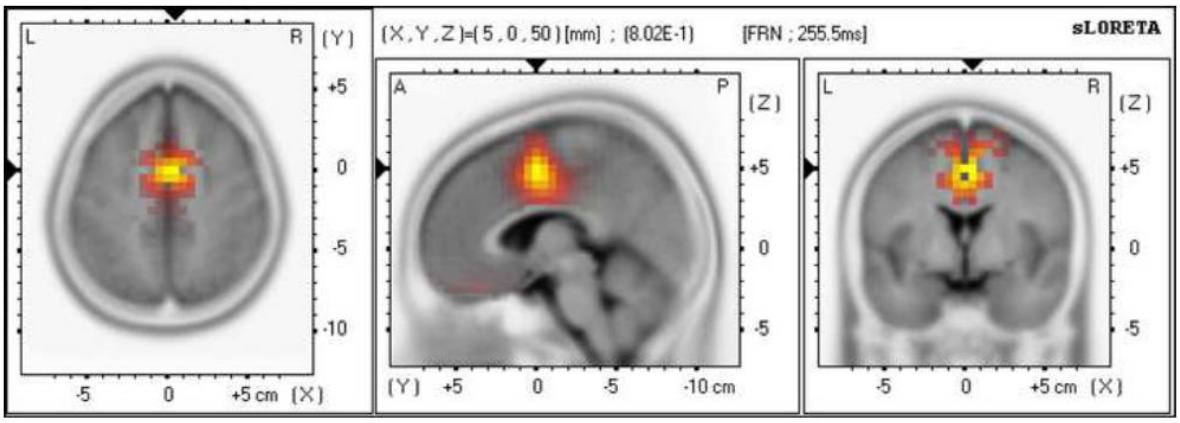

Figure 3. sLORETA source localization of the FRN loss-win difference wave at 255ms post-feedback.

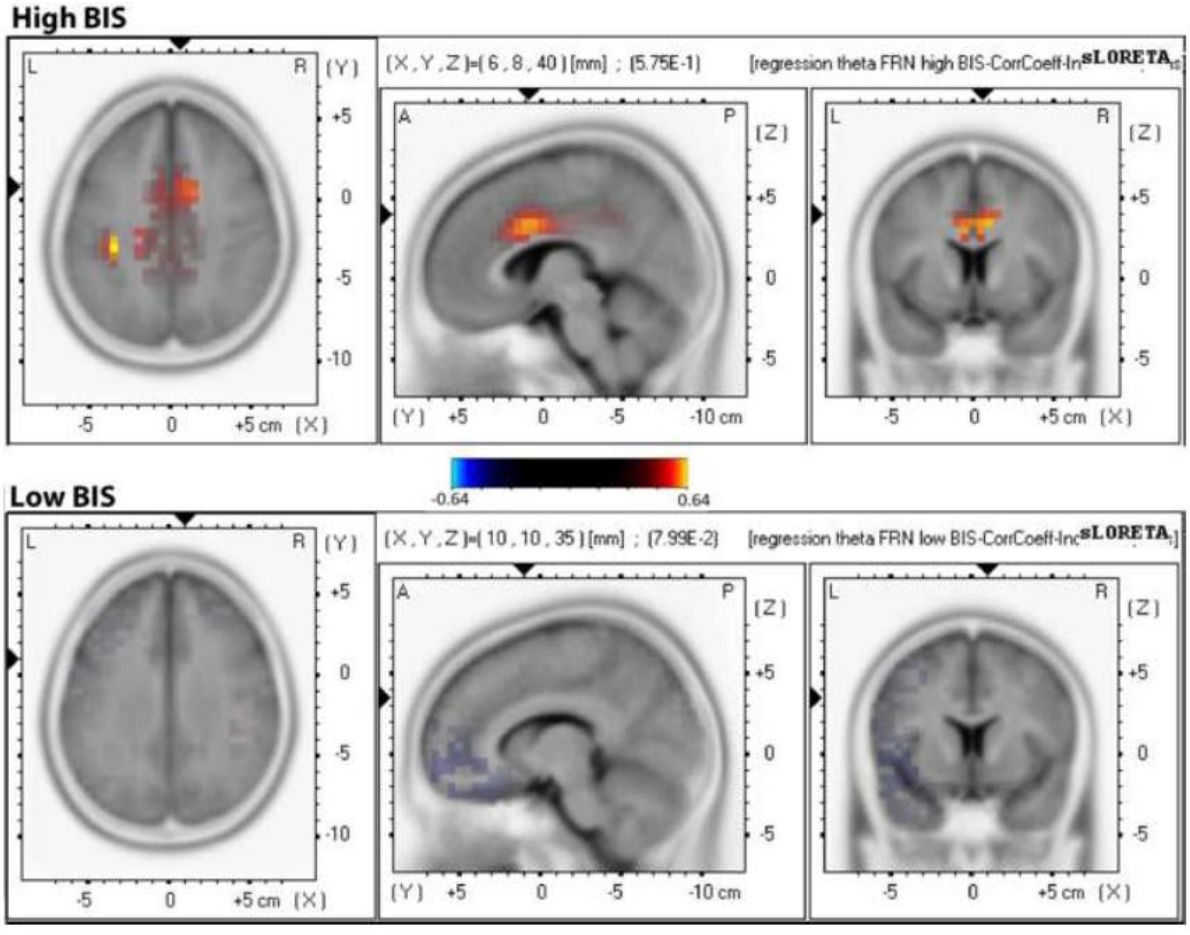

Figure 4. Clusters in the theta band that correlated with FRN amplitude for high BIS group (upper panel), and low BIS group (lower panel)

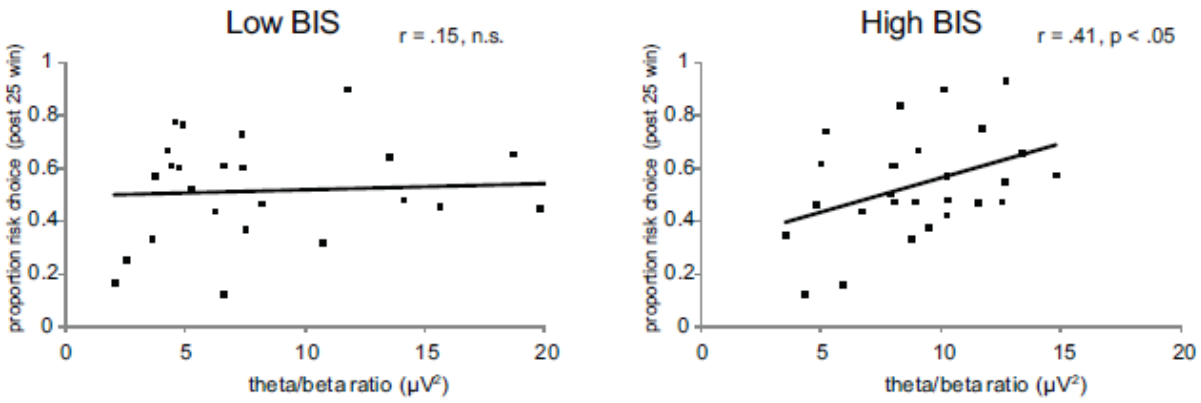

Figure 5. Correlations between theta/beta ratio and the proportion of high gambles directly following a high win trial for high and low BIS participants separately.